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CHARACTERIZING FRACTURES BY ELECTRON FRACTOGRAPHY

PART X

FRACTOGRAPHY OF NOTCH TENSILE SPECIMENS OF 4300-SERIES STEELS

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ABSTRACT

Fracture faces of round-bar notch tensile specimens of five different 4300-series steels were examined in the electron microscope. The dependence of fracture mode on carbon content and relative yield strength level was investigated. A diagram is presented to show the dominant fracture modes observed for various combinations of yield strength and carbon content.

PROBLEM STATUS

This report concludes the work on one phase of the problem; work on other aspects is continuing.

AUTHORIZATION

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INTRODUCTION

The identification of fracture modes by examination of the topography of fracture faces has been greatly advanced by use of the electron microscope. The appearances of various types of fracture surfaces such as the dimple-shaped contours of dimpled rupture, the smooth polygonal configurations of grain boundary rupture, and the river-like striations of cleavage, are known and generally accepted as characteristic of the various modes. A large body of encyclopedic data on the fracture modes in various metals and alloys under various types of stresses must be accumulated in order to define the utility of electron fractography to the development of test concepts in mechanical metallurgy, to the analysis of service failures, and to the development of new alloys or the improvement of older ones. The present investigation was intended to ascertain the variation in fracture mode of notched tensile specimens with changes in yield strength and carbon content.

Five heats of 4300-series steel of different carbon contents had been made at N. R. L. for an extensive mechanical test program directed by P. P. Puzak (1). The carbon contents, as determined by chemical analyses, were: 0.22%, 0.29%, 0.38%, 0.44% and 0.56%. Drop-weight, Charpy V-notch impact, standard tensile and round-bar notch tensile tests were performed on specimens (tempered to various strength levels) from each heat. The results of the mechanical test program were reported by Puzak (1), who had the foresight to preserve the fracture faces by immediate desiccation and who kindly made the specimens available for this study.

PROCEDURE

The fracture faces were first examined under a low-power bench microscope to observe the general macroscopic appearances and to locate obvious material flaws. The fracture faces were then replicated using cellulose acetate followed by evaporated carbon. A thorough electron microscopical examination was made of each replica, and micrographs were made depicting the topography of the fracture surfaces.

OBSERVATIONS

Examinations under the low-power microscope disclosed that with decreasing yield strength there was a trend toward: 1. A more undulating fracture surface, 2. A broader band of concentric tearing rings adjacent to the peripheries of the bars, 3. More and larger vertical splits all of which were roughly parallel in any given specimen. The areas around the mid-radii were found to be representative of the main fracture faces.

Electron microscopical examination of all replicas showed that three distinct fracture modes (Quasi-cleavage, grain boundary rupture and dimpled rupture), usually in combinations, where operative in the fracture processes of these steels. Changes in predominating fracture mode with changes in yield strength and carbon content were noted, and are shown in Table I. Electron-micrographs of the different fracture modes listed in Table I are shown in Figures 1 - 5., Rough estimates of the percent of the total fracture surface area that failed by quasi-cleavage and grain boundary rupture were made and these were plotted as functions of yield strength in Figures 6 and 7. The predominating fracture mode as a function of both yield strength and carbon content is shown in Figure 8, to indicate roughly the areas of dominance of each particular mode. These areas are not sharply defined and considerable overlapping occurs. The notch tensile strengths of the individual specimens are included in Figure 8, and it is noteworthy that the intergranular and quasi-cleavage modes are not associated with particularly low notched tensile strengths, as one might intuitively anticipate.

It may also be noted in Figure 8, that within the predominantly grain boundary and quasi-cleavage areas, the percentage of dimpled rupture increases with both increasing and decreasing yield strengths from a minimum near the center of the area. The change in dominant fracture mode is very gradual with respect to both yield strength and carbon content. For example, at 0.56% carbon the percent dimpled rupture decreases from 100% at YS = 120 KSI to a minimum of 15% at YS = 200 KSI and then increases again to 100% at YS = 242 KSI.

CONCLUSIONS

Observations under the low-power microscope revealed characteristics typical of fractures produced in notch tension tests. The concentric rings may be the areas of slow crack growth prior to the onset of rapid crack propagation of the main fracture. The vertical splits which gave rise to shear lips are probably related to voids or inclusion sites.

The electron-microscopical examination led to the following conclusions concerning the relationships of fracture mode to yield strength level and carbon content:

1. High yield-strength steels with carbon content of 0.29% and above fracture principally by large-dimple dimpled rupture.

2. Low-carbon (<0.38%)-intermediate yield strength steels fracture principally by quasi-cleavage.

3. High carbon (>0.38%)-intermediate yield strength steels fracture principally by grain-boundary rupture.

4. Low yield-strength steels, of all carbon contents investigated, fractured principally by small-dimple dimpled rupture.

The average dimple size in the dimpled rupture fracture mode decreases with:

a. Decreasing yield strength for a given carbon content.

b. Increasing carbon content for a given yield strength level.

REFERENCES

(1) P. P. Puzak, "Effect of Carbon Content and Tempering Temperatures on the Fracture Toughness of High-Strength Quenched and Tempered Steels", Ph.D. Thesis, Univ. of Md. (1961).

TABLE I

PREDOMINANT FRACTURE MODE AT VARIOUS CARBON CONTENTS

AND YIELD STRENGTH LEVELS

Carbon Content	High Yield Strength	Intermediate Yield Strength	Low Yield Strength
0.22	Quasi-Cleavage	Quasi-Cleavage	Dimpled Rupture
0.29	Dimpled Rupture	Quasi-Cleavage	Dimpled Rupture
0.38	Dimpled Rupture	Quasi-Cleavage plus Grain Boundary Rupture	Dimpled Rupture
0.44	Dimpled Rupture	Grain Boundary Rupture	Dimpled Rupture
0.56	Dimpled Rupture	Grain Boundary Rupture	Dimpled Rupture

Fig. 1A. Fracture surface of 4322 steel (yield strength ≅ 176 KPSI). Quasi-cleavage (arrow) is the predominant fracture mode. 3030X.

Fig. 1B. Fracture surface of 4322 steel (yield strength ≅ 91 KPSI). Dimpled rupture (arrow) is the predominant fracture mode. 3030X.

Fig. 2A. Fracture surface of 4329 steel (yield strength $\cong$ 188 KPSI). Dimpled rupture is the predominant fracture mode. 3030X.

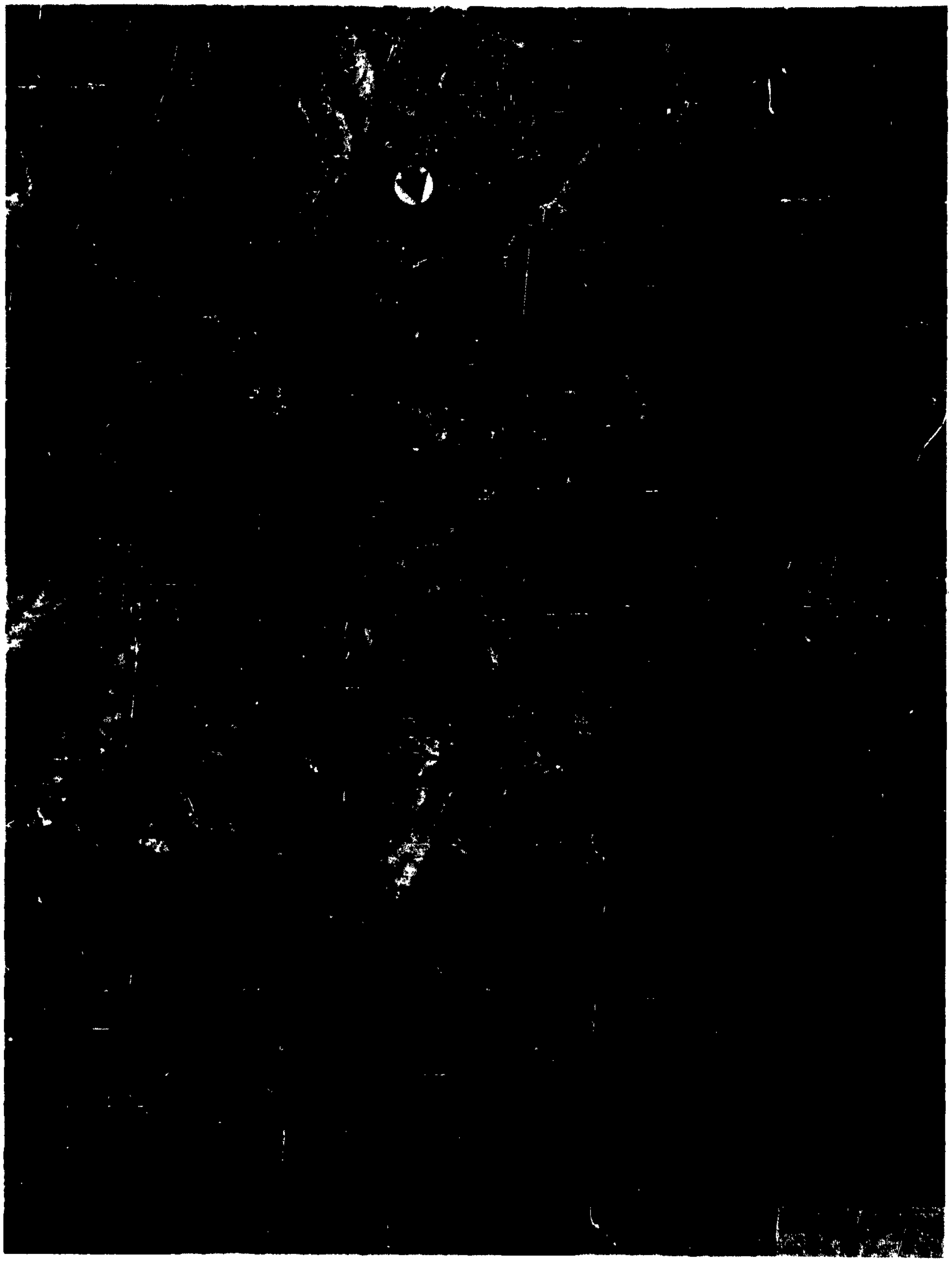

Fig. 2B. Fracture surface of 4329 steel (yield strength ≈ 182 KPSI). Quasi-cleavage (arrows) is the predominant fracture mode. 3030X.

Fig. 2C. Fracture surface of 4329 steel (yield strength $\cong$ 103 KPSI). Dimpled rupture is the predominant fracture mode. 3030X.

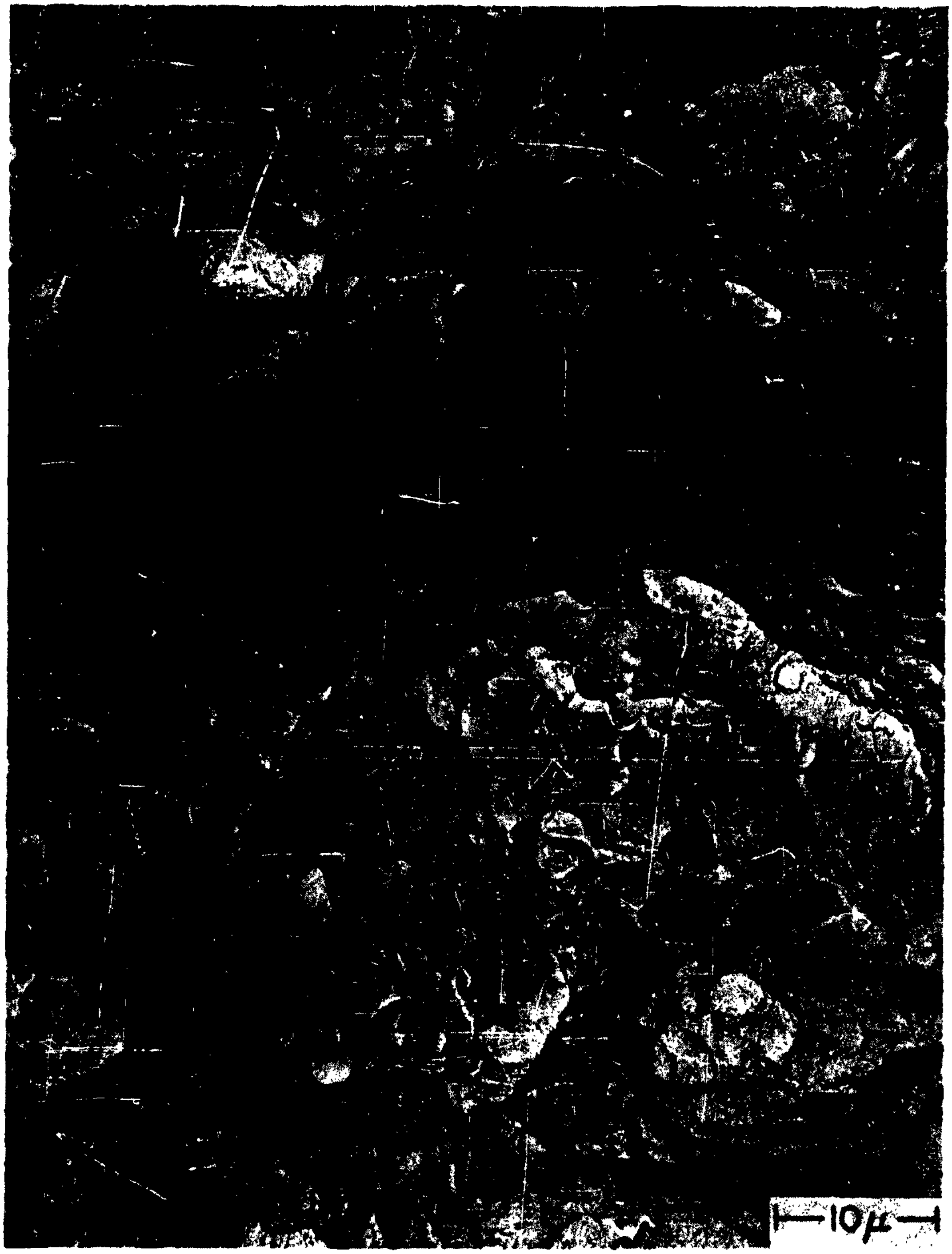

Fig. 3A. Fracture surface of 4338 steel (yield strength ≟ 223 KPSI). Dimpled rupture is the predominant fracture mode. 3030X.

Fig. 3B. Fracture surface of 4338 steel (yield strength $\cong$ 217 KPSI). Grain boundary rupture (A) and quasi-cleavage (B) are predominant fracture modes. 3030X.

Fig. 3C. Fracture surface of 4338 steel (yield strength ≅ 116 KPSI).
Dimpled rupture is the predominant fracture mode. 3030X.

Fig. 4A. Fracture surface of 4344 steel (yield strength $\cong$ 226 KPSI) Dimpled rupture is the predominant fracture mode. 3030X.

Fig. 4B. Fracture surface of 4344 steel (yield strength ≚ 190 KPSI). Grain boundary rupture is the predominant fracture mode. 3030X.

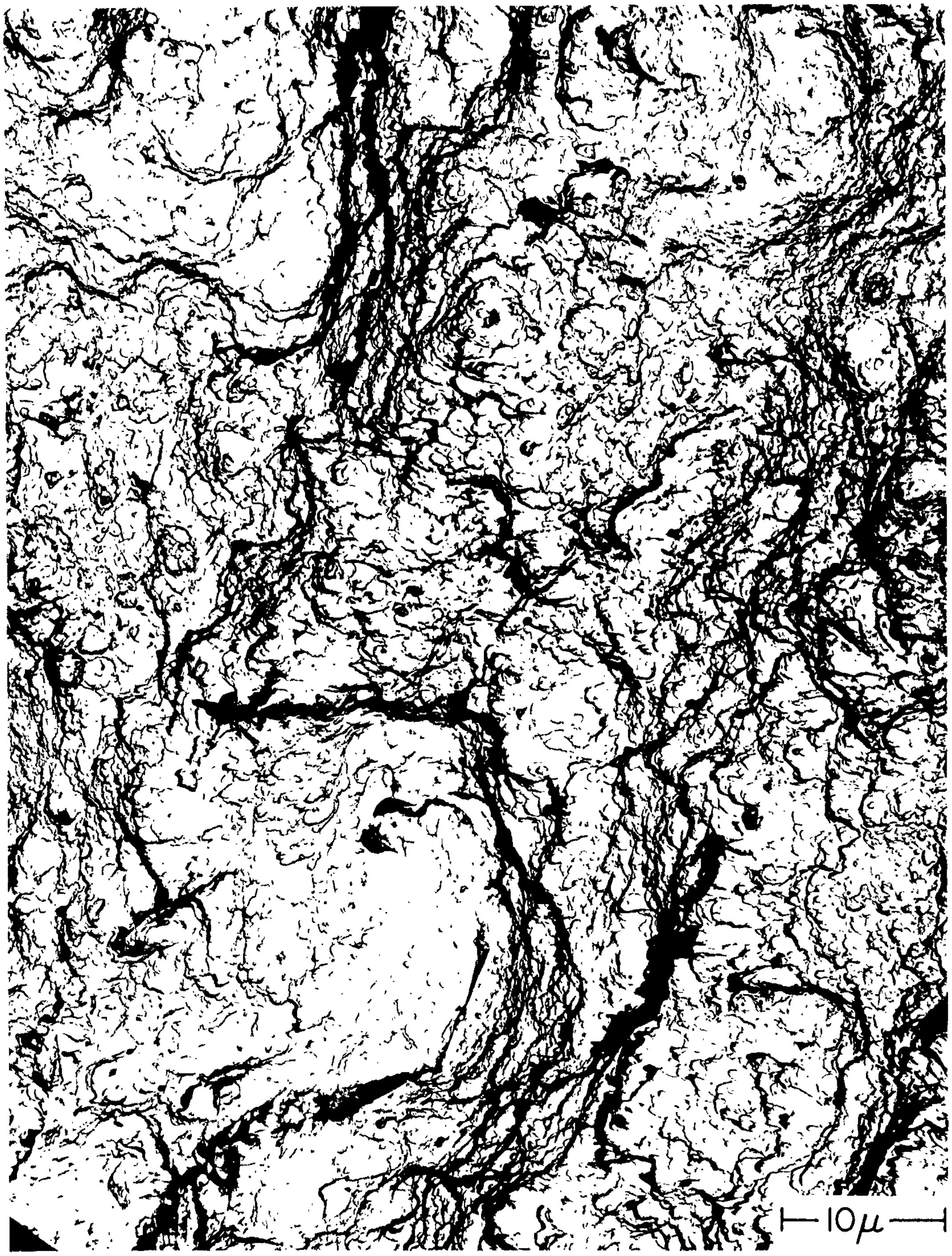

Fig. 4C. Fracture surface of 4344 steel (yield strength ≅ 114 KPSI). Dimpled rupture is the predominant fracture mode. 3030X.

Fig. 5A. Fracture surface of 4340 steel (yield strength ≅ 240 KPSI). Dimpled rupture is the predominant fracture mode. 3030X.

Fig.5B. Fracture surface of 4356 steel (yield strength ≅ 205 KPSI). Grain boundary rupture is the predominant fracture mode. 3030X.

Fig. 5C. Fracture surface of 4356 steel (yield strength ≅ 146 KPSI). Dimpled rupture is the predominant fracture mode. 3030X.

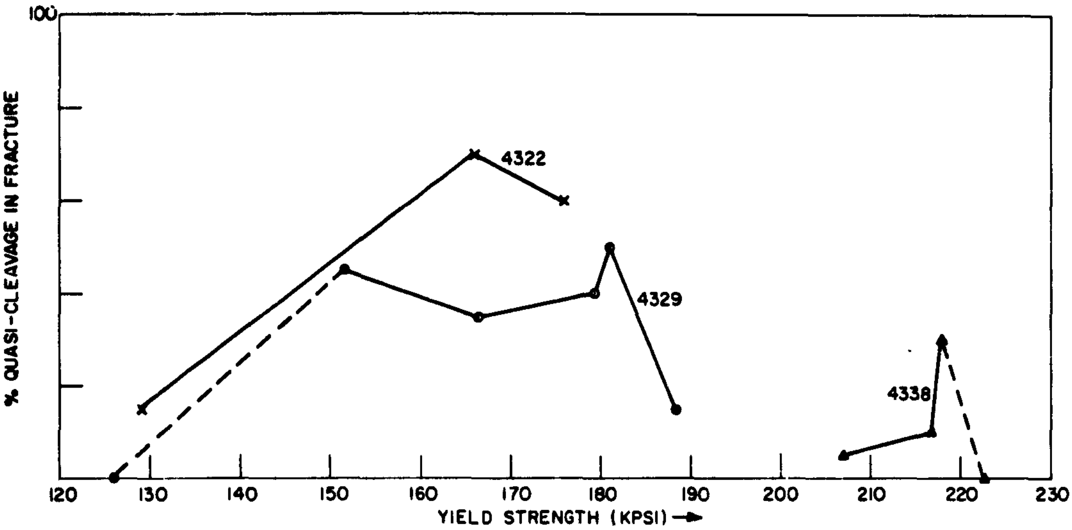

Fig. 6. Variation in percent of quasi-cleavage with yield strength in notched round tensile specimens of three carbon contents,

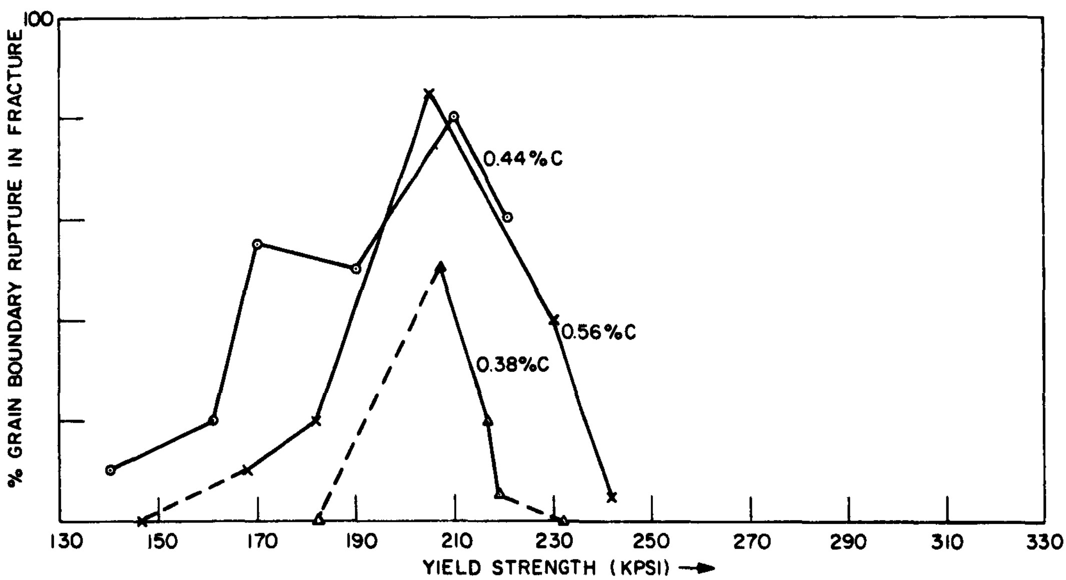

Fig. 7. Variation in percent of grain boundary rupture with yield strength in notched round tensile specimens of three carbon contents.

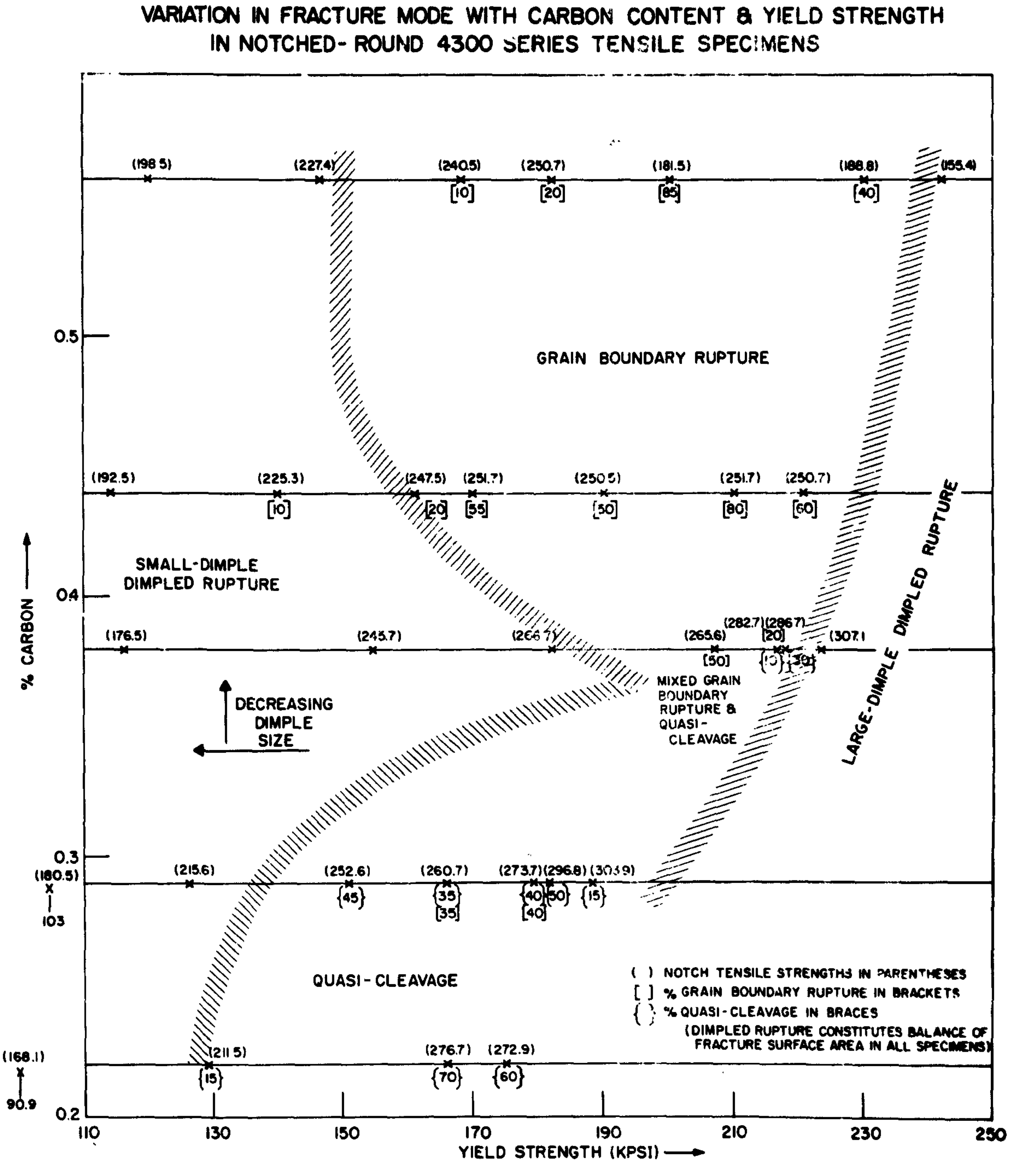

Fig. 8. Variation in fracture mode with carbon content and yield strength in notched round 4300 series tensile specimens. The notched tensile strengths are shown in parentheses and the fracture modes noted for each specimen. The boundaries shown between fracture modes are indistinct, with gradual transitions between modes.